

He II emitters in the VIMOS VLT Deep Survey: PopIII star formation or peculiar stellar populations in galaxies at $2 < z < 4.6$?

P. Cassata^{1,*}, O. Le Fèvre¹, S. Charlot², T. Contini³, O. Cucciati⁴, B. Garilli⁵, G. Zamorani⁴, C. Adami¹, S. Bardelli⁴, V. Le Brun¹, B. Lemaux¹, D. Maccagni⁵, A. Pollo^{6,7}, L. Pozzetti⁴, L. Tresse¹, D. Vergani⁸, A. Zanichelli⁴ and E. Zucca⁴,

¹ Aix Marseille Université, CNRS, LAM - Laboratoire d'Astrophysique de Marseille, 13388, Marseille, France e-mail: paolo.cassata@oamp.fr

² UPMC-CNRS, UMR7095, Institut d'Astrophysique de Paris, F-75014, Paris, France

³ Laboratoire d'Astrophysique de Toulouse-Tarbes, Université de Toulouse, CNRS, 14 Av. E. Belin, 31400 France

⁴ INAF-Osservatorio Astronomico di Bologna - via Ranzani 1, I-40127, Bologna, Italy

⁵ IASF-INAf - via Bassini 15, I-20133, Milano, Italy

⁶ Astronomical Observatory of the Jagiellonian University, ul. Orla 171, 30-244 Kraków, Poland

⁷ National Centre for Nuclear Research, ul. Hoża 69, 00-681 Warsaw, Poland

⁸ INAF IASFBO, via P. Gobetti 101, 40129 Bologna, Italy

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ABSTRACT

Aims. The aim of this work is to identify He II emitters at $2 < z < 4.6$ and to constrain the source of the hard ionizing continuum that powers the He II emission.

Methods. We have assembled a sample of 352 galaxies with a high quality spectroscopic redshift at $2 < z < 4.6$ from the VVDS Deep and Ultra-Deep surveys, and we have identified 40 He II $\lambda 1640$ emitters. We study their spectral properties, measuring the fluxes, equivalent widths (EW) and FWHM for most relevant lines, including He II $\lambda 1640$, Ly α line, Si II $\lambda 1527$ and C IV $\lambda 1549$.

Results. About 10% of galaxies at $z \sim 3$ and $i_{AB} \leq 24.75$ show He II in emission, with rest frame equivalent widths $EW_0 \sim 1 - 7 \text{ \AA}$, equally distributed between galaxies with Ly α in emission or in absorption. We find 12 (3.4% of the global population) high-quality He II emitters with unresolved He II line ($FWHM_0 < 1200 \text{ km/s}$), 13 (3.7% of the global population) high-quality emitters with broad He II emission ($FWHM_0 > 1200 \text{ km/s}$), 3 AGN, and an additional 12 possible He II emitters. The properties of the individual broad emitters are in agreement with expectations from a W-R model. On the contrary, the properties of the narrow emitters are not compatible with such model, neither with predictions of gravitational cooling radiation produced by gas accretion, unless this is severely underestimated by more than two orders of magnitude by current models. Rather, we find that the EW of the narrow He II line emitters are in agreement with expectations for a population III (PopIII) star formation, if the episode of star formation is continuous, and we calculate that a PopIII SFR of $0.1 - 10 M_{\odot} \text{ yr}^{-1}$ only is enough to sustain the observed He II flux.

Conclusions. We conclude that narrow He II emitters are either powered by the ionizing flux from a stellar population rare at $z \sim 0$ but much more common at $z \sim 3$, or by PopIII star formation. As proposed by Tornatore et al. (2007), incomplete ISM mixing may leave some small pockets of pristine gas at the periphery of galaxies from which PopIII may form, even down to $z \sim 2$ or lower. If this interpretation is correct, we measure at $z \sim 3$ a SFRD in PopIII stars of $10^{-6} M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$, higher than, but qualitatively comparable to the value predicted by Tornatore et al. (2007).

Key words. Cosmology: observations – Galaxies: fundamental parameters – Galaxies: evolution – Galaxies: formation

1. Introduction

Understanding the early phases of star formation in the Universe is a major topic of recent astrophysical investigation. In particular, despite the growing size of galaxy sam-

ples at $z > 5 - 8$, selected either through the Lyman-break technique (Bouwens et al. 2007; Bouwens et al. 2008; Bouwens et al. 2010; McLure et al. 2011; ...) or via strong Ly α emission detected in narrow band filters (Hu et al. 2004; Tapken et al. 2006; Murayama et al. 2007; Hibon et al. 2010; Hibon et al. 2012), some of which have spectroscopic confirmation (Vanzella et al. 2009; Capak et al. 2011; Curtis-Lake et al. 2012; Schenker et al. 2012), the population responsible for the reionization of the Universe at this epoch is still not identified. In this respect, zero metallicity stars and/or proto-galaxies, which should be the first structures formed in the life of the Universe and whose role in ionizing the Universe is predicted to be very important, have not been identified yet. The first population of stars formed from the pristine gas during the reionization is the so-called Population-III (hereafter Pop-III). This population is predicted to be of extremely low metallicity and to pro-

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duce strong UV ionizing continuum (Tumlinson & Shull 2000; Schaerer 2002). No evidence for Pop-III stars has been found so far. Moreover, despite the high efficiency of the “cold mode” gas accretion in cosmological simulation (Keres et al. 2005, Dekel et al. 2009), that may be enough to sustain the observed rapid increase of the Star Formation Rate Density (SFRD) of the Universe between $z \sim 8$ and $z \sim 2$, scarce evidence for gas infalling onto an overdensity has been reported so far. Steidel et al. (2010) found only partial evidence of inflow around galaxies at $z \sim 2$; Cresci et al. (2010) claimed that the inverted metallicity gradient observed in $z \sim 3$ galaxies could be due to cold flows; Giavalisco et al. (2011) detected cold gas around $z \sim 1.6$ galaxies, that is possibly infalling into an overdensity.

Coincidentally, the footprint of both PopIII star formation and gas cooling during gravitational accretion is the presence of Ly α 1216 and He II λ 1640 emission lines in the spectra of the sources. Dual Ly α 1216 and He II λ 1640 emitters have been proposed by various authors as candidates hosting PopIII star formation (Tumlinson et al. 2001; Schaerer 2003; Raiter, Schaerer & Fosbury 2010): in PopIII star formation regions, where an extreme top-heavy initial mass function (IMF) is expected, very massive stars with high effective temperatures are formed. These stars, unlike normal PopII and PopI stars, produce photons shorter of $\lambda = 228\text{\AA}$ that can ionize He^+ . In a region with primeval composition, in the absence of other metals, the H and He lines become the dominant line coolant for the gas, and thus the gas emits strong Ly α + He II emission. On the other hand, Fardal et al. (2001) showed that the pristine gas recently accreted onto an overdensity cools down emitting hydrogen or helium line radiation; Yang et al. (2006) claimed that dual Ly α 1216 and He II λ 1640 can be used to trace the infall of pristine gas onto an overdensity: if the accretion mode is “cold”, as predicted by many theoretical studies (Fardal et al. 2001; Keres et al. 2005) the gas temperature is below the halo virial temperature, reaching $T \sim 10^5\text{K}$; if the gas is pristine (zero metallicity) H and He lines are the most efficient gas coolants, and thus Ly α 1216 and He II λ 1640 emission is produced.

Strong Ly α +He II emission lines are commonly found in other astrophysical objects, such as Wolf-Rayet stars (W-R), AGN and supernovae driven winds. However, several diagnostics can be used to distinguish cooling radiation and PopIII star formation from these other mechanisms: AGN, W-R stars and emitters powered by supernovae driven winds typically show other emission lines in their spectra, such as C III and C IV (Reuland et al. 2007; Leitherer et al. 1996; Allen et al. 2008). Moreover, W-R stars are associated with strong winds, and thus produce broad emission lines (a few 1000 km/s, Schaerer 2003). Brinchmann, Pettini & Charlot (2008) showed that the broad He II emission detected in the composite spectrum of $z \sim 3$ galaxies by Shapley et al. (2003) can indeed be reproduced by W-R models. In W-R galaxies, or young star clusters with heavy star formation, He II emission may be observed in either a W-R stellar mode and broadened by the W-R winds, or in a nebular narrow-line mode as the strong UV emission from these stars photoionizes the surrounding medium (Kudritzki 2002). Nebular He II emission also appears in some star forming regions in which the source of ionisation is not clearly identified as WR or O stars, but this is a rare event in the local universe (Kehrig et al. 2011).

Unfortunately, no direct diagnostics can be used to distinguish between some extreme PopI populations, PopIII, or cooling radiation, to explain He II λ 1640 emission; rather, only indirect inference can be used to discriminate these possibilities.

Schaerer et al. (2003) predicted that a PopIII region forming stars at a rate of $1 M_{\odot}\text{yr}^{-1}$, dependent on the IMF (top-heavy or less extreme) and the metallicity ($0 < Z < 10^{-5}$), will produce He II luminosities between $\sim 1.5 \times 10^{39}$ and $\sim 5 \times 10^{41}$ erg/s. On the other hand, Yang et al. (2006) predicted that pristine gas infalling into overdensities at $z \sim 2 - 3$ would produce similar He II luminosities, between $\sim 1 \times 10^{40}$ and $\sim 1 \times 10^{41}$ erg/s. In principle, the two mechanisms predict different $L_{\text{Ly}\alpha}/L_{\text{He II}}$ ratios: around ~ 100 for the PopIII regions and around ~ 10 for the cooling radiation. However, since Ly α , unlike He II, is a resonant line with a large cross section, the observed Ly α emission depends on various aspects as the geometry of the system, its dynamical state, or the presence of dust. The combination of these effects results on an average escape fraction f_{esc} of the Ly α photons around 10% at $2 < z < 4$ (Hayes et al. 2011). However, individual galaxies at those redshift show f_{esc} values that fluctuate significantly around the average value. As a result, the observed ratio $L_{\text{Ly}\alpha}/L_{\text{He II}}$ can be very different from the intrinsic one and thus can not be used as a diagnostics.

The quest for Population III stars or gravitational cooling emission at high- z has so far been quite unproductive. Searches of dual Ly α +He II emitters beyond $z \sim 5$ are difficult, as the He II λ 1640 line is redshifted in the near infrared: Nagao et al. (2005) found no He II in a deep near-infrared spectroscopic observation of a strong Ly α emitter at $z=6.6$. New multi-objects high-performance near-infrared spectrographs coming online in the next months will give new insights on this aspect.

Several studies at $z \sim 4 - 5$ have identified objects with extremely large Ly α equivalent widths ($\text{EW}_0 > 250\text{\AA}$), that are expected in case of a top-heavy IMF, a very young age ($< 10^7\text{years}$) and/or a very low metallicity (Malhotra&Rhoads 2002; Shimasaku et al. 2006). However, there was no evidence for He II in emission in these galaxies, either in individual or in stacked spectra. A dedicated survey for dual Ly α +He II emitters at $z \sim 4 - 5$ (Nagao et al. 2008) found no convincing candidates.

Searches of zero metallicity objects at lower redshift, where observations should be, in principle, easier, have to face the question whether significant PopIII star formation is expected to take place at these low redshifts. Tornatore, Ferrara and Schneider (2007) showed that Population III star formation continues down to $z \sim 2.5$, due to inefficient heavy element transport by outflows, that leaves pockets of pristine gas untouched in the periphery of collapsed structures. In such pockets, PopIII stars can form, even if at a rate 10^4 times slower than PopII. Fumagalli, O’Meara, & Prochaska (2011) indeed detected two gas clouds with primordial composition ($Z < 10^{-4}$) at redshift $z \sim 3$.

Motivated by these predictions, some authors succeeded in identifying $1.5 < z < 3$ Ly α +He II emitters, but none could unambiguously conclude on the the powerful source of ionization producing these emission lines. Prescott, Dey & Jannuzi (2009) discovered a Ly α nebula at $z \sim 1.67$, and they concluded that W-R stars or shocks could not be the sources of ionization. Scarlata et al. (2009) studied in great detail an extended Ly α blob at $z \sim 2.38$, but could not determine whether the source of Ly α +He II emission is an AGN or instead cooling radiation.

The aim of this paper is to look for He II emitters in the VIMOS VLT Deep Survey (VVDS) Deep and Ultradeep data at $2 < z < 4.6$, checking how frequent they are. The VVDS provides a large unbiased i-band magnitude-selected spectroscopic sample of galaxies with measured redshifts (Le Fèvre et al., 2005, and Le Fèvre et al., 2013, in prep.), offering an excellent

basis to perform a census of He II emitters. On the galaxies with He II detection, we measure their properties such as line fluxes, equivalent width and line width in an attempt to constrain the mechanisms powering the emission.

Throughout the paper, we use a standard Cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ and $h = 0.7$. In Section 2 we present the observations, in Section 3 we introduce the sample of He II emitters, in Section 4 we analyze the main mechanisms that can produce He II emission and we compare them with the properties of our sample, in Section 5 we discuss our results and in Section 6 we draw our conclusions.

2. Observations

2.1. Spectroscopy

The VVDS has exploited the high multiplex capabilities of the VIMOS instrument on the ESO-VLT (Le Fèvre et al., 2003) to collect more than 35000 spectra of galaxies between $z \sim 0$ and $z \sim 5$ (Le Fèvre et al., 2005; Garilli et al. 2008, Le Fèvre et al. 2013, in prep.). In the VVDS-Deep 0216-04 field, more than ~ 10000 spectra have been collected for galaxies with $I_{AB} \leq 24$, observed with the LR-Red grism across the wavelength range $5500 < \lambda < 9350 \text{ \AA}$, with integration times of 16000 seconds, over an area of 0.62 deg^2 . In addition, the VVDS Ultra-Deep (Le Fèvre et al. 2013, in preparation) has collected ~ 1000 spectra for galaxies with $i_{AB} \leq 24.75$, obtained with LR-blue and LR-red grisms, with integration times of 65000 seconds for each grism, over an area of 0.16 deg^2 . This produces spectra with a wavelength range $3600 < \lambda < 9350 \text{ \AA}$. For both the Deep and Ultra-Deep surveys, the slits have been designed to be $1''$ in width, providing a good sampling of the $1''$ typical seeing of Paranal, and between $\sim 4''$ and $\sim 15''$ in length, which allows for good sky determination on both sides of the main target. The resulting resolution power is $R \approx 230 - 250$ for both the LR-blue and LR-red grisms, providing a theoretical spectral resolution of $\sim 22 \text{ \AA}$ at 5000 \AA . Using the calibration lamp emission line spectra, we measured a true resolution (FWHM) of $\sim 22 \text{ \AA}$, corresponding to a velocity resolution of $\sim 1150 \text{ km/s}$ at $z \sim 2.5$. However, as the atmospheric seeing during the observations was often better than the slit width, the galaxies in our sample never fill completely the slit: we measured on the 2-d spectra the FWHM in the spatial direction for the 40 He II emitters, and we found values between $0.5''$ and $1.2''$, with a typical value of $0.8''$. These values are very similar to the FWHM of the seeing, meaning that the spectra are barely resolved in the spatial direction. Assuming that objects are circular, we can assume that their spatial extent across the slit is also $0.8''$. As a result, the effective resolution in the spectral direction can be smaller than the nominal one. We have therefore taken $\sim 18 \text{ \AA}$ as the average spectra resolution, corresponding to $\sim 1000 \text{ km/s}$ at $\lambda = 1640 \text{ \AA}$ at $z \sim 2.5$.

We deconvolved the observed line FWHM into intrinsic FWHM₀ applying the simple equation:

$$FWHM_0 = \sqrt{FWHM_{obs}^2 - FWHM_{instr}^2} \quad (1)$$

where $FWHM_{instr}$ is the instrumental resolution. Assuming that $FWHM_{instr} = 1000 \text{ km/s}$ (as derived from the mean spectral resolution of 18 \AA reported above), an emitter with observed $FWHM = 1200 \text{ km/s}$ will have an intrinsic $FWHM = 663 \text{ km/s}$, and an emitter with observed $FWHM = 2000 \text{ km/s}$ will have an intrinsic $FWHM = 1732 \text{ km/s}$. Of course, with our assumption,

the conversion is meaningless for those galaxies with observed $FWHM < 1000 \text{ km/s}$.

2.2. Photometry and SED fitting

The VVDS 0216-04 field benefits from extensive deep photometry. The field was first observed with the CFH12K camera in the *BVR*I bands (Le Fèvre et al., 2004; McCracken et al., 2003), in the *U* band (Radovich et al. 2004) and in the *K* band (Iovino et al. 2005). More recent and significantly deeper observations were obtained as part of the CFHT Legacy Survey in *ugri* and *z'* (Goranova et al. 2009; Coupon et al. 2009), and as part of the WIRDS survey in *J*, *H* and *K* bands (Bielby et al., 2012). We use the T0005 data release of the CFHTLS observations, that reach 5σ point source limiting magnitudes in *i* band of $i_{AB} \approx 28$. The WIRDS observations reach a 3σ point source limit of $K_{SAB} \approx 23.5$.

We performed the spectral energy distribution (SED) fitting using the code ALF (Algorithm for Luminosity Function, Ilbert et al. 2005), that includes the routines of the code Le Phare. We used the template library from Bruzual & Charlot (2003), and we include in the fit also the dust attenuation in the form defined by Calzetti et al. (2000). The SED fitting has been performed on the observed *u**BgVriZJHKs photometric broadbands. We refer the reader to Cucciati et al. (2012) for more details. Walcher et al. (2008) demonstrated that, for a sample of galaxies with spectroscopic redshift $z < 1.2$ drawn from the VVDS sample, the SFR inferred from a similar SED fitting procedure (though with slightly worse photometry than in this work) is in good agreement with the one measured via O II and/or H α lines.

3. The He II emitters

In this study we concentrate on galaxies with secure redshifts (flags 2, 3, 4, 9, see Le Fèvre et al., 2005) in the range $2 < z < 4.6$, for which the He II line at $\lambda_{rest} = 1640 \text{ \AA}$ is redshifted to $\sim 5000 - 9200 \text{ \AA}$. The Ultra-Deep spectra cover this wavelength range completely, while the Deep ones only cover this range from $z = 2.3$ to $z = 4.6$. In total, these criteria select 352 galaxies, 148 of which are from the Deep survey. The galaxies in the sample show different lines in their UV rest-frame domain, such as Ly α (1216 \AA), Si II (1260 \AA), O I doublet (1303 \AA), C II (1334 \AA), Si IV doublet (1397 \AA), C IV doublet (1549 \AA), Al II (1671 \AA), He II (1640 \AA) and C III (1909 \AA). For each galaxy, we estimated the redshift by measuring the observed wavelength of the lines present in the observed spectrum. Since it has been observationally shown that Ly α is often redshifted with respect to interstellar lines (Steidel et al. 2010), Ly α was not considered a good tracer of the systemic redshift of galaxies. For each galaxy, we have at least ~ 3 high signal to noise interstellar lines to perform the redshift determination.

In Figure 1 we report the average spectrum resulting from the stack of all the 352 galaxies at $2 < z < 4.6$, as well as the stack of the 207 galaxies at $2 < z < 3.5$ (for which the He II line falls in the region covered by the Blue Grism), and we compare them with the stack of about 1000 Lyman Break Galaxies by Shapley et al. (2003, hereafter S03). The stack has been produced running the *scombine* routine in IRAF, which produced a variance weighted average. The spectra are normalized to the median flux density estimated between $\lambda = 1500 \text{ \AA}$ and

⁰ <http://www.cfht.hawaii.edu/~arnouts/LEPHARE/lephare.html>

Line	Stack narrow		Stack broad		Stack possible		Stack all 352	
	EW ₀	FWHM	EW ₀	FWHM	EW ₀	FWHM	EW ₀	FWHM
Ly α	-7.5	1750	8.0	1021	-9.6	2097	3.9	1002
Si II	-1.5	–	-1.7	984	-1.2	565	-2.0	1203
O I	–	–	-2.2	1130	-3.8	1222	-2.8	1349
C II	-0.7	912	-1.5	893	-2.0	784	-2.0	1185
Si IV ₁	-2.5	1276	-2.2	1659	-1.8	1076	-1.9	1550
Si IV ₂	-2.7	1824	-1.1	1093	-1.5	1148	-1.2	1404
Si II	-1.0	912	-1.8	1495	-2.4	1185	-1.5	1112
C IV	-6.0	2995	-3.7	1586	-4.5	1932	-3.3	1786
He II	3.9	966	2.7	1914	3.3	2220	0.9	1677
C III	7.7	1586	3.8	1768	–	–	1.7	2151

Table 1. Rest-frame equivalent widths and FWHM for absorption and emission lines in the composite spectra of Fig. 1 and 6.

$\lambda = 2000\text{\AA}$. A sigma clipping algorithm (lsigma=3, hsigma=3) is applied during the stacking process and the spectra are combined using mean stacking.

In Table 1 we report equivalent widths and line widths (FWHM) for the most relevant absorption and emission lines of the stacked spectra. In both composite spectra, a broad He II emission at $\lambda = 1640\text{\AA}$ is evident: we measure rest-frame equivalent widths of $\sim 0.9\text{\AA}$, and FWHMs $\sim 1500\text{--}1800\text{ km/s}$. The presence of the He II line in the composite of galaxies at $2 < z < 4.6$ implies that the He II emission is a quite common feature in the spectra of star forming galaxies at these redshifts. Our composite spectrum, and in particular the one with galaxies at $2 < z < 3.5$ only, is remarkably similar to the S03 composite. The only differences are that the S03 composite has stronger Ly α emission, stronger P-Cygni features around N V, O I and C IV lines and a slightly stronger He II emission (EW₀ $\sim 1.5\text{\AA}$).

We then visually inspected the 352 spectra to identify *bona-fide* He II emitters responsible for the emission feature in the combined spectra. We excluded all galaxies for which the He II emission at 1640\AA falls in a spectral region dominated by bright OH airglow emission lines, which dominate the background at $\lambda > 7500\text{\AA}$, and thus are not easy to subtract from the combined object+sky spectra in low-resolution spectra. We identified a preliminary list of 114 potential emitters, and we cleaned it removing the less convincing cases, (objects with lines at the location of OH airglow emission, or at spectral location with known higher background noise) which resulted in 40 “bona-fide” He II emitters. Among these, 9 are from the DEEP survey and the remaining 31 from the Ultra-DEEP one. Three of them were identified as AGN during the redshift measurement process. In order to test the robustness of our sample and to estimate the fraction of “false positive” lines that could be due to some stochastic noise peak, we multiplied all of the 352 spectra by -1 and we re-checked them to look for “fake” He II lines. We found a list of 10 “fake” emitters, and after cleaning this sample as we did for the real one, we ended up with 2 possible emitters only. This experiment shows that 5% of our 40 emitters (at the most) could be fake detections.

For each He II emitter, we measured the Equivalent Width (EW), the line flux, the line observed FWHM and the S/N of the continuum around the He II line using the *onedspec* task of IRAF. We then divided the sample in 4: the *high-quality* narrow He II emitters (12 objects, with FWHM_{He II} $< 1200\text{ km/s}$); the *high-quality* broad He II emitters (13 objects, with FWHM_{He II} $> 1200\text{ km/s}$); the *possible* He II emitters (12 objects, for which the detection is not certain, based on the line shape, position with respect to sky lines and/or the line S/N ra-

tio); AGN (3 objects). We chose a discriminating observed He II FWHM of 1200 km/s because this corresponds to an intrinsic (deconvolved) FWHM $\sim 663\text{ km/s}$, a very conservative lower limit for the line width expected in the case of Wolf-Rayet stars (see Section 4 and 4.2).

We show the spectra of the 40 He II emitters, for the 4 groups mentioned above, in Figure 2 (the *secure* emitters with narrow He II emission), Figure 3 (the *secure* emitters with broad He II emission), Figure 4 (the three AGN) and Figure 5 (the *possible* He II emitters).

For each individual spectrum we identify at least 2 lines, that have been used to determine the spectroscopic redshift (for about 90% of the objects we identify 3 or more absorption and/or emission lines). The most common feature in the spectra is the doublet Si II+C IV at 1526 and 1549\AA . For some of the objects coming from the Deep survey (labelled as 20xxxxxxx) the Ly α region is not covered. It can be also seen that for 14 He II emitters the Ly α line is in absorption. We also remark that C IV is in absorption for all objects, except for one of the AGN (for the other 2 C IV is not in the covered spectral range).

We also produced stacked spectra for the four families of He II emitters, following the same procedure used for the composite of all the 352 He II emitters. The stacked spectra are shown in Fig. 6, in comparison with stellar population models by Maraston et al. (2009) and Eldridge & Stanway (2012). We will discuss the comparison between data and models in Section 5. The measurements of the rest-frame equivalent width EW₀ and FWHM are listed in Table 1.

The stack of the good quality narrow He II emitters clearly shows a narrow He II emission FWHM_{observed} $\sim 1000\text{ km/s}$ (hence unresolved at our resolution), with a rest-frame Equivalent Width EW $\sim 4\text{\AA}$, comparable to those of individual spectra. The stack of the good quality broad He II emitters shows also a broad He II line, with FWHM_{observed} $\sim 1800\text{ km/s}$ (hence 1500 km/s intrinsic) and EW $\sim 2\text{\AA}$. Interestingly, the stack of the possible He II emitters also shows a clear He II emission, with EW = 3.2\AA and FWHM_{observed} $\sim 2200\text{ km/s}$ (1960 km/s intrinsic).

From both a visual inspection of the composite spectra in Fig. 6 and from the analysis of the equivalent widths and line widths in Tab. 1 it is clear that narrow and broad He II emitters have completely different properties. Not only the He II line width is different (FWHM ~ 1000 vs 1600 km/s), but also the strength of the interstellar absorption lines varies significantly between the two families. One striking difference is that the narrow-He II composite spectrum has very weak low ionization interstellar lines (Si II, O I, C II, EWs $\sim -1\text{\AA}$) with respect to the strong high ionization ones (Si IV, C IV, EWs $\sim -5\text{\AA}$); compared

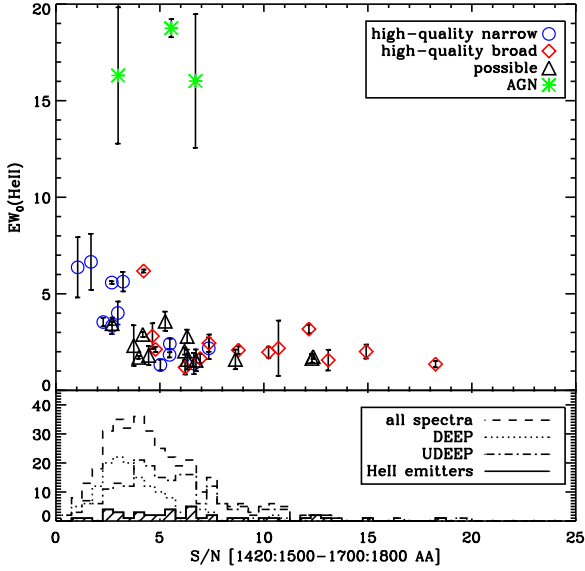


Fig. 7. *Top panel:* Rest-frame equivalent width of the He II $\lambda 1640$ line as a function of the average S/N ratio per resolution element of the spectra in the two regions 1420–1500Å and 1700–1800Å, for the 40 galaxies with detected He II in emission. The blue circles, red diamonds, black triangles and green asterisks represent the high-quality emitters with narrow He II lines, the high-quality emitters with broad He II lines, the possible emitters and the objects classified as AGN, respectively. *bottom panel:* histogram of the average S/N ratio at 1420–1500Å and 1700–1800Å for all the 352 galaxies in the sample (long dashed line), for the DEEP and UDEEP spectra (dotted and dot-dashed, respectively) and for the 40 galaxies with He II in emission (continuous filled histogram).

to the narrow-He II composite which shows “normal” low-to-high ionization ratios (similar to the ones for the stack of all galaxies at $2 < z < 4.6$). Moreover, the C IV line for the stack of the narrow emitters has a red wing absorption that is not observed in the other stacks.

In Figure 7 we report the rest-frame equivalent width EW_0 of the He II lines as a function of the signal to noise ratio per resolution element measured in the two regions 1420–1500 and 1700–1800Å. These two regions are contiguous to the He II line, and as they do not contain any spectral feature, they provide a reference measurement of the continuum emission. Apart from the three AGN, that have typical $EW_0 \sim 15 - 20$ Å, the other He II emitters in the sample have $1 \lesssim EW_0 \lesssim 7$ Å. These values are in general agreement with the rest-frame equivalent widths of the He II line measured by Scarlata et al. (2009) for a Ly α blob at $z = 2.373$ ($EW_0(\text{He II}) \sim 3.5$ Å) and by Erb et al. (2010) for a low-metallicity galaxy at $z \sim 2.3$ ($EW_0(\text{He II}) \sim 2.7$ Å). Prescott, Dey, & Jannuzi (2009) found instead a nebula at $z \sim 1.6$ with much more powerful He II emission, with $EW_0(\text{He II}) \sim 35$ Å.

Below $S/N \sim 4$, the EW_0 and S/N are correlated: the smaller the S/N, the higher the Equivalent Width. This is not surprising, since objects with $S/N < 4$ have barely detected continua. It is also clear that narrow He II emitters have continuum S/N that is lower than that of the broad ones.

In the bottom panel of Fig. 7 we compare the continuum S/N ratios of the He II emitters with the S/N of the full 352 galaxies

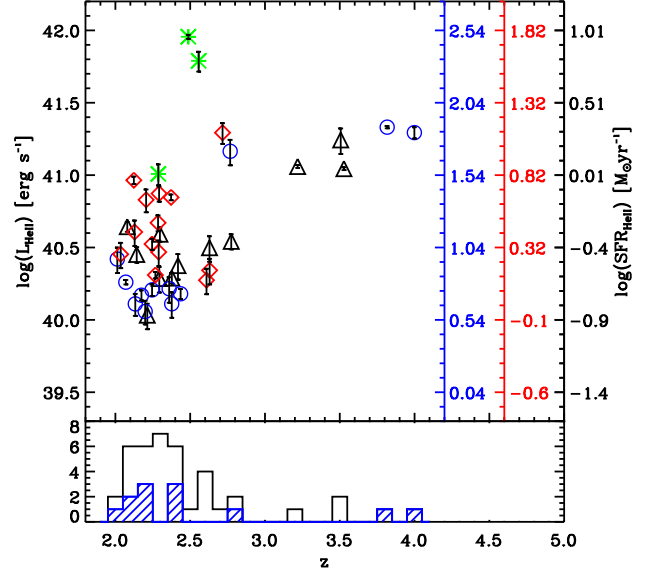


Fig. 8. *Top panel:* Luminosity of the He II line as a function of the redshift for the 40 identified He II emitters in our sample. The blue circles, red diamonds, black triangles and green stars represent the high-quality emitters with narrow He II lines, the high-quality emitters with broad He II lines, the possible emitters and the objects classified as AGN, respectively. The three axis on the right represent the Star Formation Rates needed to produce such He II luminosities, for a top-heavy IMF with Salpeter slope extending from $1M_\odot$ to $500sM_\odot$ and metallicities $Z=0$ (black), $Z=10^{-7}$ (red) and $Z=10^{-5}$ (blue), using the conversion in Schaerer 2003 (see text). *Bottom panel:* Redshift distribution of the 40 He II emitters (empty histogram) and of the high quality ones (filled histogram).

sample. Objects drawn from the UDEEP survey have typically larger S/N ratios than those drawn from the DEEP one, as expected from scaling the exposure times, with the total distribution extending from $S/N = 0$ (on the continuum, for emission-line only spectra) to $S/N \sim 20$ and peaking around $S/N \sim 4$. The 40 He II objects with He II emission have a S/N distribution that is similar to the one for the 352 parent galaxies: we found He II emission both in objects with faint and bright continuum.

In Figure 8 we show the luminosity of the He II line as a function of the redshift for the 40 He II emitters in the sample. Two of the AGN are the most luminous objects in He II, with luminosities up to $10^{42} \text{ erg s}^{-1}$, while the other emitters have $10^{40} < L_{\text{He II}} < 10^{41.5} \text{ erg s}^{-1}$.

In the same figure, the He II luminosities are converted in the star formation rates needed to produce such He II emission, where it is assumed that the He II emission is due to star formation that is happening in a gas region of primeval composition. We applied three conversions calculated by Schaerer (2003): a top-heavy IMF with Salpeter slope extending from $1M_\odot$ to $500M_\odot$, and three metallicities $Z=0$, $Z=10^{-7}$ and $Z=10^{-5}$. From these calculations we infer that, if He II originates from a region with zero metallicity, the star formation rate needed to produce the observed He II line luminosity is only $0.1 - 3 M_\odot \text{ yr}^{-1}$. We remark also that adding just a few metals changes this estimate considerably: for $Z=10^{-7}$ and $Z=10^{-5}$ the pro-

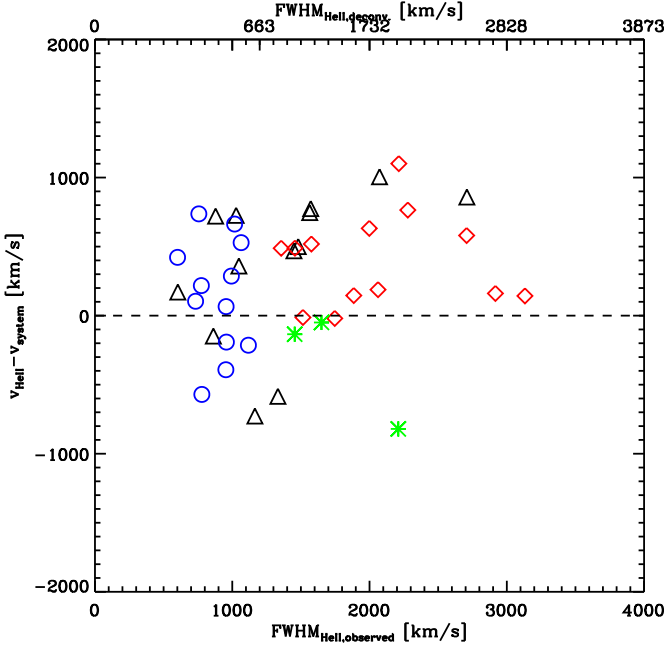


Fig. 9. For the 40 He II emitters, the velocity difference between the centroid of the He II line and the systemic redshift as versus the FWHM, in km/s, of the He II line. The bottom axis is linear and reports the observed FWHM, while the top axis is converted in deconvoluted FWHM. The color code of the symbols is the same as in Fig. 8.

duction of He II photons is much less efficient, so we need 10 to 50 times more star formation to produce the observed He II line flux. In any case, no matter the metallicity, the SFR inferred from the He II lines under the assumption that He II is the result of star formation only are always smaller than the values measured for the individual galaxies from SED fitting (see Figure 10).

In Figure 9 we show the width of the He II line (FWHM, expressed in km/s, observed and intrinsic on the bottom and top axis, respectively) as a function of the velocity difference between the He II line and the systemic redshift (measured from the position of the absorption lines, see Section 2), together with the distribution of the two quantities. The distribution of the observed FWHM extends from 600 km/s to 3000 km/s, with ~ 10 emitters having a FWHM formally smaller than the spectral resolution of the instrument. As we explained in Section 2, this is not unexpected: the nominal resolution of ~ 1000 km/s has been measured on the spectra of a lamp that uniformly illuminates the $1''$ slit, while our galaxies have spatial extent of $\sim 0.8''$ (FWHM). We conclude that galaxies with observed $\text{FWHM}(\text{He II}) \leq 1000 \text{ km/s}$ are spectrally unresolved.

By our definition the narrow and broad He II emitters have observed $\text{FWHM} < 1200$ and $\text{FWHM} > 1200$ km/s, respectively, corresponding to intrinsic $\text{FWHM} \geq 663 \text{ km/s}$. This limit has been chosen because Wolf-Rayet stars are always associated with strong stellar winds, with speeds around or larger than 1500 km/s: He II emitters powered by W-R stars have expected line widths around or above that limit. The possible He II emitters span a broad range of line widths, but only 3 out of 12 have $\text{FWHM} > 1500 \text{ km/s}$.

In Fig. 9 we also report the velocity difference Δv between the He II line and the systemic velocity, calculated measuring the position of the He II line in the rest-frame spectra. As the

system systemic redshift is centered on the interstellar lines, this correspond to the velocity difference between the He II line and those lines. We see that the high-quality narrow He II emitters have $\Delta v_{\text{He II}}$ values spanning from -1000 to 1000 km/s, with the distribution well centered on $\Delta v_{\text{He II}} = 0$. On the other side, high-quality broad He II emitters always have $\Delta v_{\text{He II}} > 0$. We have run a 2-d KS test, and we found that the two distribution are different at a 90% level. This additional difference support the hypothesis that broad and narrow He II emitters are two distinct families.

4. Analysis

In the previous section we described the properties of a sample of 40 He II emitters discovered among 352 $z > 2$ galaxies of the VVDS Deep and Ultradeep surveys. In this Section we analyze and discuss such properties with the aim of constraining the mechanism that produces the He II line. As discussed in the Introduction, only a few astrophysical mechanisms can power the He II nebular emission, as a powerful ionizing source is needed to produce photons with energies $E > 54.4 \text{ eV}$, that can ionize He^+ .

4.1. AGN

The extremely blue continuum of active galactic nuclei is hard enough to produce photons with $e > 54.4 \text{ eV}$, thus ionizing He^+ and powering the He II emission feature. Similarly to the case of W-R stars, typical spectra of AGN (both Type I and II) have other emission lines in their spectra, such as C IV and Si II, that can be used as diagnostics. Typical narrow line Type II AGN have $< \text{C IV}/\text{He II} > = 1.50$ (McCarthy 1993; Corbin & Boroson 1996; Humphrey et al. 2008; Matsuoka et al. 2009). Moreover, Type I AGN (those AGN in which the active nucleus is directly exposed to the observer) have line widths of 2,000 km/s and above.

Three He II emitters in our sample have been classified as AGN. Object 910359136 has been discovered in the Ultradeep part of the survey, and thus is covered both with the Blue and the Red grism. This produces a rest-frame spectral window that covers all the spectrum from Ly α to C III. The morphology of this object in the CFHTLS images is diffuse, with no point like components, suggesting that the broad line region is completely obscured from our line of sight. The modest line widths ($\text{FWHM}_{\text{obs}} \sim 1400 \text{ km/s}$, corresponding to intrinsic $\text{FWHM}_0 \sim 1000 \text{ km/s}$) supports this interpretation. We measure line ratios $\text{Ly}\alpha/\text{He II} = 11.5 \pm 1.6$ $\text{C IV}/\text{He II} = 1.97 \pm 0.35$ and $\text{C III}/\text{C IV} = 0.72 \pm 0.25$, that are remarkably similar to the average values for radio galaxies $< \text{Ly}\alpha/\text{He II} > = 9.8 \pm 5.69$ and $< \text{C IV}/\text{He II} > = 1.50 \pm 0.56$ (McCarthy 1993; Corbin & Boroson 1996; Humphrey et al. 2008). Matsuoka et al. (2009) also found $\text{C IV}/\text{He II} = 1.34^{+0.57}_{-0.4}$ and $\text{C III}/\text{C IV} = 1.14^{+0.43}_{-0.31}$ for Narrow Line Regions at $2 < z < 2.5$ and with $41.5 < L_{\text{He II}} < 42.5$. We can conclude that object 910359136 is indeed a Type II AGN.

The other two objects classified as AGN (20366296 and 20273801) are instead drawn from the VVDS Deep survey, so they are only observed with the red grism, and their rest-frame spectra only cover the region between $\lambda = 1600$ and $\lambda = 2600 \text{ \AA}$, a spectral domain which covers only from He II to C III. The He II and C III lines are broad ($\sim 2000 \text{ km/s}$), and the sources are point like in the CFHTLS images; thus, it is likely that they are Type I AGN, in which the nucleus is directly exposed to the line of sight directed to the observer.

Are the remaining 37 He II emitters powered by an AGN? From a visual inspection of Figs. 2, 3 and 5 it is evident that for the remaining He II emitters in our sample C IV is either undetected (910252781, 910248649, 910301515, 910248649, 910191609, 910362042, 20215115, 910248329, 910285698, 910246547 and 20191386) or in absorption (all the other cases). This implies C IV/He II ratios always smaller than 0.5: the ratio is an upper limit for the objects with no C IV detection and it is negative for the objects with C IV in absorption. Since in typical AGN we expect a C IV line always stronger than the He II one (McCarthy 1993; Corbin & Boroson 1996; Humphrey et al. 2008; Matsuoka et al. 2009), we can exclude the AGN as a plausible source of ionization for all these 37 He II emitters. We also stress that it is very unlikely that a highly obscured AGN, like the ones discovered by Civano et al. (2011), is responsible for the He II emission in our objects. If those objects do not have in their spectra the emission lines typical of unobscured AGN because these have been absorbed by dust, there is no reason why the He II line would not have been absorbed too.

Finally, it is also possible that a normal Type II AGN is buried deep into our objects, producing at the same time the He II emission line and a C IV emission that is not visible as it would be hidden in the C IV absorption typical of the host galaxies. However, since AGN do not produce low-ionization lines such as Si II $\lambda 1527$, this scenario would significantly reduce the C IV absorption while leaving Si II unchanged, ultimately altering the C IV/Si II ratio. Since we do not see objects with strange C IV/Si II ratio (i.e. objects with a stronger Si II than C IV absorption) we can exclude this possibility.

4.2. Wolf-Rayet stars

Another possible mechanism powering He II emission is Wolf-Rayet stars. Wolf-Rayet stars are evolved and massive stars ($> 10M_{\odot}$), descendent of the O stars, with surface temperatures between 30,000 and 200,000 K, that are losing mass very rapidly. They typically show strong and broad emission lines, produced by their dense and fast stellar winds (Leitherer et al. 1995; Leitherer, Robert & Heckman, 1996; Crowther 2007). The extremely high surface temperatures of such stars can produce the energetic photons needed to power the He II emission. The He II line width, as for the other emission lines, is expected to be broad, with a FWHM on the order of few thousands of km/s (Schaerer 2003).

The Wolf-Rayet stars are commonly divided in WC, whose spectra are dominated by Carbon lines, and WN stars, with spectra dominated by Nitrogen lines. Both classes show strong and broad He II $\lambda 1640$ emission, with typical line widths in excess of 1000 km/s (Crowther 2007). In WC stars the C IV $\lambda 1549$ /He II $\lambda 1640$ ratio is always greater than one (Sander, Hamann & Todt, 2012), while in WN stars this ratio is lower than 1, with cases with no C IV emission at all (Hamann, Grafener & Liermann, 2006). While the abundance of WC and WN stars is about the same in the Milky way, WN are 10 times more common than WC stars in low metallicity objects (Massey & Holmes 2002). In addition, Crowther & Hadfield (2006) showed that in low metallicity environments the He II flux and line width are reduced, with line FWHMs as low as 850 km/s. Chandar, Leitherer & Tremonti 2004 and Hadfield & Crowther identified the most extreme WR galaxy in the local Universe: NGC3125 shows a strong He II line, with EW $\sim 7\text{\AA}$ and FWHM ~ 800 km/s.

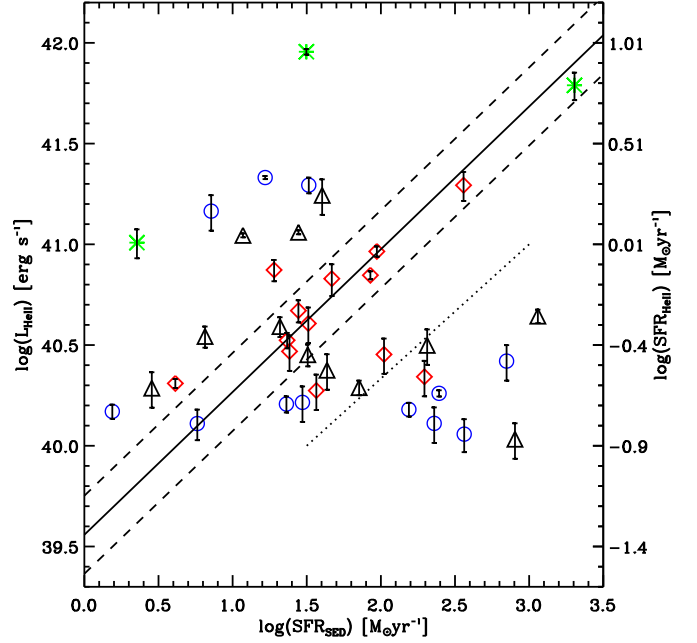


Fig. 10. For the 40 He II emitters, we compare the SFR measured fitting the broad-band SED of galaxies and the luminosity of the He II line. The continuous and dashed lines show a linear best fit (with scatter) to the high-quality He II emitters with broad emission (red diamonds). The dotted line is the expected correlation between these two quantities according to the cooling radiation model by Yang et al. (2006). The color code of the symbols is the same as in Fig. 8. The right axis report the star formation rate needed to produce such He II luminosity (as for Fig. 8), assuming a top-heavy IMF with Salpeter slope extending from $1M_{\odot}$ to $500sM_{\odot}$ and metallicity $Z=0$.

We show in Figure 11 the blow-up of the region around the He II line for the narrow and broad stacks, in comparison with gaussians with different widths, in order to evaluate the ability of our data, that have a typical velocity resolution of 1000 km/s, of resolving the line widths for the most extreme W-R objects. We overplot a gaussian with observed FWHM=1000 km/s, the width that we measure for the He II line in the stack of the narrow emitters, and that again corresponds to our spectral resolution. We also overplot a gaussian with intrinsic FWHM=800 km/s (the narrowest He II in the local Universe produced by W-R stars), that corresponds, after convolving with the instrumental resolution of 1000 km/s, to an observed FWHM=1250 km/s. It is evident that this gaussian is wider than the observed He II line, and that in principle we would be able to identify a line with such FWHM observed at our resolution. For comparison, we also report two gaussians with observed FWHM of 1500 and 1800 km/s, corresponding respectively to intrinsic FWHM of 1200 and 1500 km/s at our resolution. The latter corresponds to the width that we measure for the He II line in the broad composite.

Including the W-R phase in stellar population synthesis models is not an easy task, as it heavily depends on the number of very massive stars (and thus on the IMF), on the atmosphere and wind models of very massive stars, and as we mentioned earlier, on the metallicity of the environment. Shapley et al. (2003), who first detected a broad He II emission in the composite of 1000 $z \sim 3$ galaxies, interpreted the He II line as the signature of W-

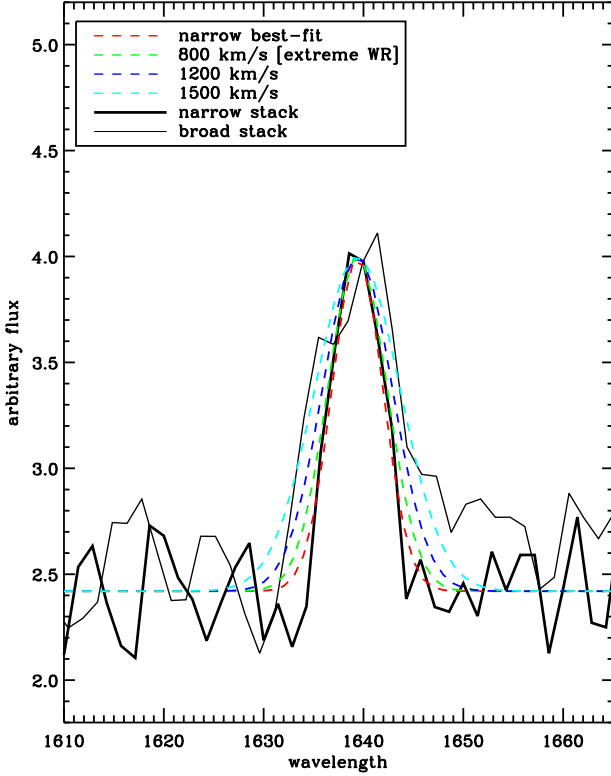


Fig. 11. We show a blow-up of the region around the He II line for the stack of the narrow emitters (black thick line) and the stack of the broad ones (black light line). We report the gaussian with an observed FWHM=1000 km/s, the width that we measure for the He II line in the narrow stack. For comparison, we show also other gaussians, with intrinsic FWHMs of 800 km/s (green dashed), 1200 km/s (blue dashed) and 1500 km/s (cyan dashed). These line widths, once convoluted with our 1000 km/s resolution, produce observed FWHM of 1250, 1500 and 1800 km/s, respectively.

R stars, but then failed to identify a stellar model that could at the same time reproduce the strength of the line and the P-Cygni C IV emission. Brinchmann, Pettini & Charlot (2008) combined the state of the art population synthesis models with observations of local galaxies in the Sloan Digital Sky Survey, generating a model that can, with a half solar metallicity, reproduce the observational features of the S03 composite spectrum.

Eldridge & Stanway (2012) recently published a grid of synthetic spectra, produced using a new stellar population synthesis code that includes binary massive stars. These models naturally incorporate a W-R phase, and predict strong He II emission about 50 Myr after the burst of star formation (the age for which the number of W-R stars is maximal). The strength of the He II line depends on the metallicity, being maximal for $Z=0.004$. In these models (ES12 hereafter), the He II emission is broad and it is always accompanied by a C IV absorption+emission P-Cygni line. Using these models, invoking a Carbon reduction with respect to other metals, Eldridge & Stanway (2012) can reproduce quite nicely the C IV line profile and the He II emission in the S03 spectrum.

In Fig. 6 we checked whether or not we could reproduce the properties of our stacked spectra with ES12 models. However we found that, whatever the metallicity, such models never have

strong enough low-ionization lines (O I, C II and Si II) that we observe in the stack of the broad and possible He II emitters. So, we decided to combine the ES12 models with the synthetic high-resolution UV spectra by Maraston et al. (2009), that conversely have stronger low-ionization lines (but no He II emission). We stress that we did not try to perform any rigorous fitting procedure, but we simply compared the predictions by a combination of these two sets of models with our composite spectra. The only restriction we imposed is that the metallicity of the components used to build our synthetic spectra is always subsolar (as it is expected to be at $z \sim 2.5$).

The models are superimposed to the composite spectra in Fig. 6. For the stack of the narrow He II emitters, that does not have strong low-ionization lines, we simply chose a E12 model, with a continuous star formation of $1 M_{\odot} \text{yr}^{-1}$ lasting 100 Myr and metallicity $Z=0.004$ (but an instantaneous burst 10 Myr old and the same metallicity produces a similar synthetic spectrum). For the broad He II emitters, we build a more complicated “ad-hoc” (and possibly unphysical) model: we combined a 150 Myr old burst of star formation with metallicity $Z=0.01$ from Maraston et al. (2009), with a second burst of star formation, with metallicity $Z=0.004$ and age=10 Myr, from the E12 library. Finally, for the stack of the possible emitters, we produced a similar synthetic spectrum to the one used for the broad composite, with only a slightly younger second component from the E12 library. We stress that these are not the “best” possible models: rather, they are only one of the many combinations that come close to reproduce the features of our composite spectra.

Starting from the narrow composite, it is clear that the overall shape of the spectrum is quite well reproduced by the synthetic model. The model reproduces quite well the absence of low-ionization lines (O I, Si II and C II), and the strength of the Si IV absorption feature at $\sim 1400 \text{\AA}$. However, the He II emission in the model is significantly broader ($\sim 2000 \text{ km/s}$) than in the composite (even though the EW is similar), and the shape of the C IV line is completely different, with the model predicting a P-Cygni profile that we do not observe in the stack. We remark that other models in E12 library are also neither able to reproduce the narrow He II line that we see in our composite, nor the absence of C IV P-Cygni profile.

On the other side, our ad-hoc models for the broad and possible He II emitters reproduce quite nicely the strength, shape and width of the He II line. Moreover, the shapes of the C IV lines in the model and in the composite spectrum are qualitatively similar, and all the other absorption lines are quite well reproduced.

The outcome of this analysis is that we were unable to reproduce the properties of the narrow He II emitters with the state-of-the-art stellar population models including W-R stars. On the other hand, although more refined modeling might be required, we can reproduce the main spectral features of the broad emitters with stellar models including a specific treatment of the W-R phase.

We remark that the lack of broad He II emitters with a negative Δv between the He II line and the systemic velocity (see Fig. 9), is compatible with the W-R scenario. In fact, it is expected that if the He II emission originate in the fast winds of a W-R star, the profile of the line is the typical P-Cygni profile (Venero, Cidale, & Figuelet 2002). It is also worth noting that a correlation between the star-formation rate of the galaxy and the number of W-R stars (and thus the He II luminosity) is expected for the W-R scenario, with the only caution that the W-R phase might be very short, and would not match the global star formation rate of the galaxy. In Figure 10 we compare the Star Formation Rate measured from fitting the SED of galaxies (see

details in Section 2.2) and the luminosity of the He II line: interestingly, we observe a correlation between the luminosity of the He II line and the Star Formation Rate for the galaxies in the high quality broad emitters category (see Figure 10), in broad agreement with predictions by models.

4.3. Gravitational cooling radiation from gas accretion

Gravitational cooling radiation from gas accreting onto dark matter haloes is another mechanism that can produce Ly α +He II emission lines, as predicted by many theoretical papers. Keres et al. (2005) showed that about half of the gas infalling onto dark matter potential is heated to temperatures $T \sim 10^4 - 10^5$: at these temperatures, the gas is expected to cool via line emission, in particular Ly α and He II (Yang et al. 2006). The Ly α line is in principle expected to be the strongest line, but its strength strongly depends on the radiative transfer of Ly α photons, as well as on the geometry and dynamics of the system; as a result, the Ly α line is easily destroyed. On the other side, He II emission should always be observed, and its luminosity should correlate with the Star Formation Rate of the galaxy the gas is falling into: intuitively, the more gas falls onto the galaxy, the higher the He II emission and thus the higher the SFR. The correlation is tighter assuming that the infalling gas is optically thin, and the predicted scatter is larger if the gas is optically thick (Yang et al. 2006).

Another prediction of such a model is that the He II line is expected to have widths not larger than 300 km/s, and the He II emission is expected to be less extended than that of the Ly α line (Yang et al. 2006; Haiman, Spaans & Quataert 2000). However, such models assume primordial composition for the infalling gas; the presence of metals can change the cooling efficiency and thus affect the strength of the He II line.

With the spectral resolution of our observations $FWHM_{intrinsic} \sim 660$ km/s we are only able to say that the widths of the narrow He II emitters are broadly consistent with line width of ~ 300 km/s predicted by the models (Yang et al. 2006). Moreover, galaxies with a “resolved” He II line (i.e. galaxies with $FWHM_{He II} > 1200$ km/s) are not compatible with the theoretical predictions for the cooling radiation scenario. Unfortunately, the spatial resolution of our spectra ($FWHM_{seeing} = 0.8''$ at the best) does not allow us to check if the He II and Ly α emission (where present) have different spatial extents. Interestingly, we find that the C IV line profile of the narrow He II emitters in the composite spectrum shows a red absorption wing. In the context of accretion, this could be interpreted as the signature of infalling gas.

However, we saw in Fig. 10 that, for the narrow He II emitters, we do not observe any correlation between the He II luminosity and the overall star formation rate of the galaxies, in disagreement with the predictions by Yang et al. (2006).

Another test that we can perform is to compare the number density of He II emitters above a given He II Luminosity with the predictions of the models: since the gas accretion is ubiquitous in cosmological simulations, models predict number density as high as 0.1 He II emitters per cubic Mpc at $z \sim 2 - 3$ with He II Luminosity $L_{He II} > 10^{40}$ erg/s (Yang et al. 2006). We calculated the number density of He II in our sample (excluding the broad emitters, that are probably powered by W-R stars) applying the classical V/V_{max} method (Avni & Bahcall 1980), and weighting each galaxy by the photometric sampling rate (basically the ratio between the number of galaxies of a given magnitude that have been spectroscopically observed). The total volume sampled by the UltraDeep (Deep) survey between $z = 2$ and $z = 3.5$ is about

$10^{6.3} (10^7) \text{ Mpc}^3$, respectively. The number density that we measure for our sample is $\sim 10^{-4} \text{ gal/Mpc}^3$, thus 2 – 2.5 orders of magnitudes smaller than the value expected by the simulations.

We therefore conclude from this indirect argument that it seems unlikely that our 40 He II emitters are powered by cooling radiation. However, we note that to make accretion models compatible with our observations, some dramatic reduction in the cooling radiation output, by about 2 orders of magnitude, would be needed in the simulations.

4.4. Pop III star formation

Star formation in metal-free or very low metallicity regions is another mechanism that is able to produce the extremely energetic photons needed to ionize He^+ and thus power the He II emission. Many authors suggested that PopIII star forming regions can be found looking for dual Ly α +He II emitters (Tumlinson et al. 2001; Schaerer 2003; Raiter et al. 2010). Such models predict extremely large equivalent widths for both Ly α and He II: Schaerer (2003) for example expects, for a burst of star formation, $EW(Ly\alpha) = 600 - 1500 \text{ \AA}$ and $EW(He II) = 20 - 100 \text{ \AA}$ (according to the metallicity, from $Z=0$ to $Z=10^{-5}$, and the IMF). However, such large EWs are sustained only for 2 Myr at the most, and the equilibrium values reached in the case of a constant star formation are much smaller: for a top-heavy IMF and extremely low metallicities ($Z < 10^{-5}$), the EW for the Ly α and He II lines are $\sim 300 - 400 \text{ \AA}$ and $\sim 5 - 15 \text{ \AA}$, respectively (Schaerer 2003). We remark that the equivalent width of the He II line for such a model strongly depends on the metallicity, and drops to virtually zero at $Z > 10^{-5}$. The typical ratio between the strength of the He II and Ly α line that the models predict also depends on the metallicity as well as the IMF: for a top-heavy IMF and zero metallicity this ratio is around $He II/Ly\alpha \sim 0.1$ (Schaerer 2003; Raiter et al. 2010). Unfortunately, the Ly α is resonant, and the Ly α photons can be easily destroyed, as noted above, so the predictions for the Ly α luminosity and EW are highly uncertain.

The distribution of $EW(He II)$ for all He II emitters in our sample (except AGN) as shown in Fig. 7 is $EW \sim 1 - 8 \text{ \AA}$, values that are similar to those expected for an event of continuous PopIII star formation (Schaerer 2003; Raiter et al. 2010). We showed in Fig. 8 that the SFR needed to power the He II fluxes that we observe in our galaxies are not so extreme: as long as the IMF is top-heavy (as it seems reasonable for PopIII star formation) and the metallicity is close to zero we find values of $0.1 - 10 M_{\odot} \text{ yr}^{-1}$.

In Fig. 10 we showed that there is no correlation between the SFR measured for the individual galaxies and the He II line luminosity. Moreover, from Fig. 10 we also showed that, assuming again that the He II emission is powered by PopIII star formation, the SFR in PopIII stars needed to generate the observed He II luminosities is always smaller (by ~ 2 orders of magnitude) than the SFR measured from fitting the SED. These two findings together imply that, if the nebular He II emission is really powered by PopIII star formation, it is happening in a small fraction of the volume of the galaxy containing some pristine gas and not in the galaxy as a whole. This would imply that the observed integrated spectra are a mix of two components: 1) normal star-forming moderate-metallicity stellar populations comprising a majority (90%) of the SF activity, and 2) PopIII stellar populations producing the ionized He, comprising a small fraction of the global star formation. This implies that the EW of the He II line is somewhat diluted in the integrated spectrum:

if the “host” spectrum had a continuum 100x brighter than the PopIII component at 1640Å, the EW of the He II line in the total spectrum would be 100x smaller than the intrinsic PopIII value.

From Fig. 9 we also saw that the He II emitters in our sample show a quite large range of He II line widths: 12 He II emitters have intrinsic $\text{FWHM}_{\text{He II}} < 660 \text{ km/s}$ and have velocity differences between the He II line and the system well distributed around zero. These He II emitters are not compatible with the WR scenario, in which the He II line is expected to be broadened by stellar winds, and are more compatible with the PopIII scenario. Conversely, the He II emitters with broad He II line are instead inconsistent with the PopIII scenario, which would produce narrow He II emission, and are instead more likely to be powered by W-R stars (as explained in the previous section).

Another prediction of the PopIII model that we can test is the star formation rate density in PopIII stars at $z \sim 2.5$, the median redshift of our sample. Tornatore, Ferrara & Schneider (2007) predict that, although the metallicity in the center of overdensities is rapidly enriched by star formation feedback, zero metallicity regions can survive in the low density regions around the large overdensities even down to $z \sim 2$. In particular, at $z \sim 2.5$ Tornatore, Ferrara & Schneider (2007) predict a PopIII SFRD of $3 \times 10^{-7} M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$. If we make the conservative assumption that only the 12 high-quality He II emitters with narrow He II emission in our sample (excluding the possible He II emitters or a fraction thereof) are powered by PopIII star formation, and we use the conversion between He II Luminosity $L_{\text{He II}}$ and PopIII SFR for a top-heavy IMF and zero metallicity calculated by Schaerer (2003) we get a SFRD $\sim 10^{-6} M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$, a factor 3 only above the prediction by Tornatore, Ferrara & Schneider (2007). This value is in broad agreement with the one derived by Prescott, Dey & Jannuzi (2009), who found SFRD $\sim 3.3 \sim 10^{-7} M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$, based on the discovery of a $\text{Ly}\alpha + \text{He II}$ nebula at $z = 1.67$. We conclude from this analysis that the SFRD derived from the observed He II assuming it is produced by PopIII stars is in broad agreement with predictions from the model of Tornatore, Ferrara & Schneider (2007), but that, if this is indeed the mechanism in place, models would need to be iterated on to match the observed SFRD.

4.5. Peculiar stellar populations

In the local Universe several HII regions showing nebular He II emission have been identified (Schaerer, Contini & Pindao 1999; Izotov & Thuan 1998; Guseva & Izotov 2000; Kehrig et al. 2011). For many of these regions the spectra show the features typical of W-R stars, that are thought to be the source of the strong ionizing continuum (see Sect. 4.2), but some are not clearly associated with neither W-R nor O-B stars (Kehrig et al. 2011).

A nebular He II component is also observed in the spectra of galaxies (de Mello et al. 1998; Izotov et al. 2006; Shirazi & Brinchmann 2012; Shapley et al. 2003; Erb et al. 2010). Once again, for many of these objects, especially at low metallicity, the nebular He II emission is not accompanied by any W-R signatures, and thus the W-R scenario can not fully explain the origin of such nebular He II emission.

The origin of the nebular He II emission in these objects is puzzling. Kudritzki (2002) showed that not only W-R, but also certain O stars, are hot enough to produce nebular He II emission. Brinchmann, Kunth & Durret (2008) claimed that at low metallicity the main source of nebular He II emission appears

to be O stars, arguing for less dense stellar winds that can be optically thin and thus be penetrated by the ionizing photons. However, the ability of O stars to produce nebular He II emission is still debated, as some local nebulae do show narrow He II emission but no O neither W-R stars (Kehrig et al. 2011).

Another possibility is that at low metallicity massive stars rotate fast enough to evolve homogeneously (i.e. Meynet & Mader 2007) thus producing higher surface temperatures. However, observational evidences for this scenario have not been reported so far.

Post-AGB stars are also claimed to be able to produce nebular He II emission (Binette et al. 1994). In this scenario, these authors demonstrate that 100 million years after a strong burst of star formation, the dominating source of ionizing photons becomes post-AGB stars, and that their combined radiation field is sufficient to ionize HeII. However, even assuming that our galaxies are as massive as $10^{11} M_{\odot}$, and that all the stellar mass has been formed during an initial burst of star formation, the He II luminosities produced by post-AGB stars would be 2–3 orders of magnitude smaller than those observed for our sample.

If the physical process responsible for nebular He II in the local universe, whatever it turns out to be, is similar to the process at work at $z \sim 3$, we note that there must have been a strong increase of the frequency of this phenomenon, or its timescale, as we observe more than 3% of the global galaxy population at $z \sim 3$ with narrow He II, while this number is much lower at $z \sim 0$.

4.6. Other mechanisms

Shocks by supernova driven winds have been proposed by many authors (Taniguchi & Shioya 2000; Mori, Umemura, & Ferrara 2004) as the possible ionization source powering the so called $\text{Ly}\alpha$ blobs (Steidel et al. 2000). It is then reasonable to consider whether this mechanism can be the source of ionization producing the He II emission as well. However, fast shock models always predict C IV in emission (Dopita & Sutherland 1996; Allen et al. 2008), with C IV/He II ratios much higher than those measured for our sample ($0.1 < C \text{ IV}/\text{He II} < 4$, depending on the shock velocity). We can therefore exclude that the bulk of our He II emitters are powered by supernova winds.

5. Discussion

In the previous section we reviewed the mechanisms that are able to produce the very energetic photons ($e > 54.4 \text{ eV}$) needed to ionize He^+ , and that thus can power the He II emission, and we compared what the models of such mechanisms predict with the properties of our He II emitters.

As we discussed in Section 4.1, it is unlikely that, apart from the three certain AGN, the remaining 37 He II emitters are powered by an AGN, as C IV is always undetected or in absorption (Fig. 2, 3 and 5), while for typical NLR it is expected to be in emission and always stronger than He II (McCarthy 1993; Humphrey et al. 2008). With a similar argument, we can also exclude that the source of ionizing photons are the fast winds produced by supernovae. Similar conclusions (although less robust) were drawn by Prescott, Dey & Jannuzi (2009) and Scarlata et al. (2009), who identified $\text{Ly}\alpha + \text{He II}$ emitters at $1.5 < z < 2.5$.

Shapley et al. (2003) presented the stack of 1000 spectra of galaxies at $z \sim 3$, in which they detected a broad He II emission ($\text{FWHM} \sim 1500 \text{ km/s}$). Due to the broad He II line, and to a clear

signature of fast winds (i.e. the C IV P-Cygni profile in their composite), they interpreted the He II emission as the evidence of a rich W-R population in their sample. More recent studies confirmed this claim (Brinchmann, Pettini & Charlot 2008; Eldridge & Stanway 2012). We saw in Fig. 1 that the composite of our 352 galaxies at $2 < z < 4.6$ is quite similar to S03 composite, so we could be tempted to draw similar conclusions about the source of the He II emission.

However, we saw that our He II emitters sample is quite heterogeneous, with as many objects with narrow He II emission as with broad. The two families have quite different properties: the narrow He II emitters have weaker low-ionization lines (O I, C II and Si II) than the broad ones; the narrow stack shows a red absorption wing in the C IV line that is not observed at all in the composite of the broad emitters.

From a direct comparison with modern stellar population synthesis models that include the W-R phase (Fig. 6), we conclude that such models can reproduce, at least qualitatively, the spectral features of the composite of the broad He II emitters, mixing components of different ages and metallicities. Conversely, such models can not reproduce the main features of the narrow stack: although with the appropriate combination of metallicity and age we can reproduce the EW of the He II line, such models always predict a broad He II line and a C IV P-Cygni line.

Another piece of information comes from the comparison of the SFR of the galaxies (as measured from the SED fitting) and the He II luminosity. The broad He II emitters do show a positive correlation, as it would be expected for the W-R scenario, assuming that the higher the star formation, the more W-R stars. No correlation at all is observed for the narrow ones.

Putting all this evidence together, we can say that the properties of the broad He II emitters can be, at least qualitatively, explained by the W-R scenario. The narrow emitters, instead, are a different family for which the W-R scenario does not work, and thus an alternative explanation is required.

We have identified three main processes which could be the cause of the He II emission in the spectra with narrow He II emission: gravitational cooling radiation, PopIII star formation and the presence of a peculiar stellar population. As indicated in Section 4.3 the He II luminosities measured from our galaxies are compatible with the ones predicted by the model by Yang et al. (2006); however, we do not see any correlation between the total SFR of the galaxies and the strength of the He II line, as predicted by such a model. Moreover, the number density of He II emitters that we derive is two orders of magnitude smaller (at least) than the prediction by Yang et al. (2006). To make models compatible with our observations would therefore require either that *all* galaxies at these redshifts are He II emitters with $EW \sim 4\text{\AA}$, which is excluded by our observations, or that models overpredict the number density of He II emitters by more than two orders of magnitude.

As discussed in Section 4.4, all observables for the narrow He II emitters are compatible with the predictions of a PopIII scenario, (and this hypothesis could also be valid for some of the possible He II emitter population), if we assume that the star formation event is happening in pockets of pristine gas that either survived at the periphery of the galaxies or just recently accreted, hence concerning small volumes and not the full volume of the galaxies. It is quite striking that the SFRD in PopIII stars that we derive from these emitters is in broad agreement with the model by Tornatore, Ferrara & Schneider (2007) at $z \sim 3$, the factor 3 difference between the two indicating that some further adjustments to the model may be necessary.

We also noted in Sect. 4.5 that various classes of objects with nebular He II emission and no W-R signatures have been identified in the local Universe. Although no convincing explanation for the origin of the He II emission has been found so far, these objects have indeed similar properties to our narrow He II emitters, and we can not exclude that they are all powered by the same mechanism. The fact that these objects are quite rare in the local Universe (Kehrig et al. 2011; Shirazi & Brinchmann 2012) and more frequent in our sample at high redshift (3–5% depending on the possible He II class, see below) may simply reflect the evolution of the star formation rate density of the Universe (that is at its peak around the median redshift of our galaxies) and the evolution of the average metallicity of the Universe.

We were only able to compare our results with a small number of previous studies. Scarlata et al. (2009) found He II emission connected to an extended Ly α blob at $z \sim 2.2$. Similarly to the bulk of our emitters, they did not detect C IV nor N V in emission, as expected in the case the nebular emission is due to AGN activity. They concluded that the most plausible scenario for the He II emission is the cooling radiation, that can at the same time explain the width of the He II line and the lack of other emission lines. Prescott, Dey & Jannuzi (2009) also found a large Ly α +He II nebula at $z \sim 1.67$. However, they found a rest-frame EW for the He II line of $\sim 35\text{\AA}$, much larger than the typical values of our sample; moreover, they detect C IV in emission in their spectrum (even though weaker than He II). These two findings suggest that their object is different from the bulk of our galaxies. In the end, they can not constrain the mechanism powering the He II emission in their object. Erb et al. (2010) thoroughly analyze the UV-optical rest-frame spectrum of a galaxy at $z=2.3$, in which they detect the He II line, with a rest-frame equivalent width $EW_0=2.7\text{\AA}$. Thanks to their high resolution spectroscopy ($\sigma_V \sim 200$ km/s) they can study in details the shape of the He II line, finding that 75% of the He II flux comes from a broad component (FWHM ~ 1000 km/s) and 25% from a narrow, unresolved component. While they conclude that the broad emission has probably a stellar origin (W-R stars), the narrow one is indicative of a hard ionizing source, possibly a very low metallicity star forming region.

To summarize, we have identified a rich population of star forming galaxies with He II emission: some show a broad He II emission, and can easily be explained by standard W-R populations; some have narrow He II emission, and they could be the high redshift counterparts of the local objects displaying nebular He II emission. Various mechanisms, more or less plausible, have been proposed to explain the He II emission in these objects (see Sect. 4.5), and in this paper we show that PopIII star formation is another mechanism that can reproduce the properties of such objects. With the current stellar population models (especially for the most massive stars and low metallicities) and with the current observations we are not able to further constrain the real mechanism.

6. Conclusions

In this paper we have reported the discovery of 40 He II $\lambda 1640$ emitters, discovered in a sample of 352 VVDS galaxies with $2 < z < 4.6$. Our main findings are the following:

1. We showed that He II emission is a quite common feature in the spectra of $2 < z < 4.6$ galaxies: 40/352 galaxies (12%) have He II in emission in their spectra, with $EW_0 = 1 - 7\text{\AA}$. We also showed that not all of the He II emitters have Ly α

- in emission: on the contrary, we report for the first time the discovery of 17 He II emitters with Ly α line in absorption.
- The rest-frame EW for the He II line in our spectra is moderate; apart from 3 AGN, for which we find $EW_0 \sim 15 - 20$, we find $EW_0 \sim 1 - 7$, similar to the values expected for PopIII stars, for a continuous episode of star formation in a zero-metallicity region, assuming a top-heavy IMF, but also consistent with the EW expected for gas accretion.
 - Apart from the 3 AGN, we never detect C IV in emission in the spectra of the He II emitters. In about 30% of the cases C IV is undetected, and in all the other cases it is in absorption. We interpret this as an evidence that the He II emission in most of our galaxies is not powered by AGN or super-novae winds.
 - If we isolate the He II emitters with broad He II line ($FWHM_{obs} > 1200 km/s$), we do observe a correlation between the SFR of the whole galaxy (as measured by fitting the UV part of the SED) and the He II line luminosity. The composite spectrum of such objects is, at least qualitatively, reproduced by stellar population synthesis models including W-R stars. We conclude that for these objects the He II emission is most likely powered by W-R stars.
 - The radiation produced by gravitational cooling does not seem to play a role in producing the He II emission in our sample. For the narrow emitters, we see no correlation between the global SFR of each galaxy determined from SED fitting and the luminosity of the He II lines, as it would be expected for this scenario. Moreover, we measure a number density of He II emitters with $L_{He II} > 10^{40} erg s^{-1}$ of $\sim 10^{-4} Mpc^{-3}$, while the predictions for the cooling radiation scenario are 2 – 2.5 order of magnitude higher. This implies that either these cooling radiation simulations overestimate the number density of He II emitters, or that some mechanism somehow lowers the efficiency of the cooling radiation, which results in fainter He II fluxes.
 - If we assume that the He II emission originates from a PopIII star forming region and we convert the He II luminosity into SFR using a simple recipe by Schaerer (2003), we find that a SFR of $0.1 - 10 M_{\odot} yr^{-1}$ is enough to sustain the observed He flux. The SFR derived from this PopIII hypothesis is always smaller (by 2 order of magnitudes on average) than the global SFR measured from the SED fitting. This implies that the He II emission could originate from a relatively small volume of pristine gas which could be distributed around the galaxies, uncontaminated by the metals mixing processes, and in which PopIII stars are currently forming. On the other hand, considering that PopIII star formation is powering, as a conservative lower limit, the narrow He II emitters, we find a SFRD in PopIII stars of $10^{-6} M_{\odot} yr^{-1} Mpc^{-3}$, only 3 times higher than the value predicted at $z \sim 2.5$ by Tornatore, Ferrara & Schneider (2007).
 - The narrow He II population has similar properties to a rare class of local objects (both individual nebulae and galaxies) which display nebular He II emission. A clear mechanism for the origin of the nebular He II line in these objects has still to be identified, and we can not exclude that this mechanism is the low redshift tail of the PopIII star formation observed in the $z \sim 3$ galaxies.

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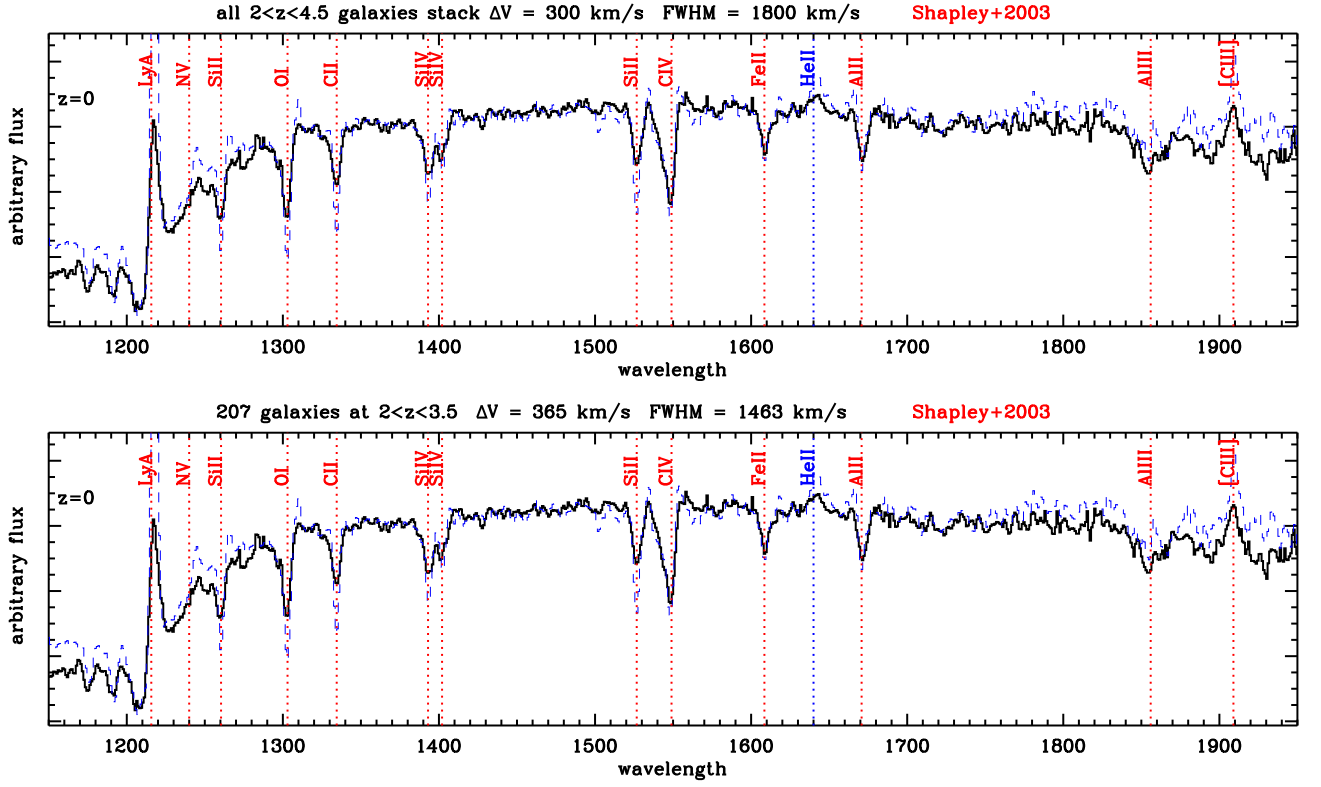


Fig. 1. Stack of all 352 spectra at $2 < z < 4.6$ (*top panel*) and stack of the 207 spectra at $2 < z < 3.5$ (*bottom panel*), in comparison with the composite spectrum by Shapley et al. (2003), in blue.

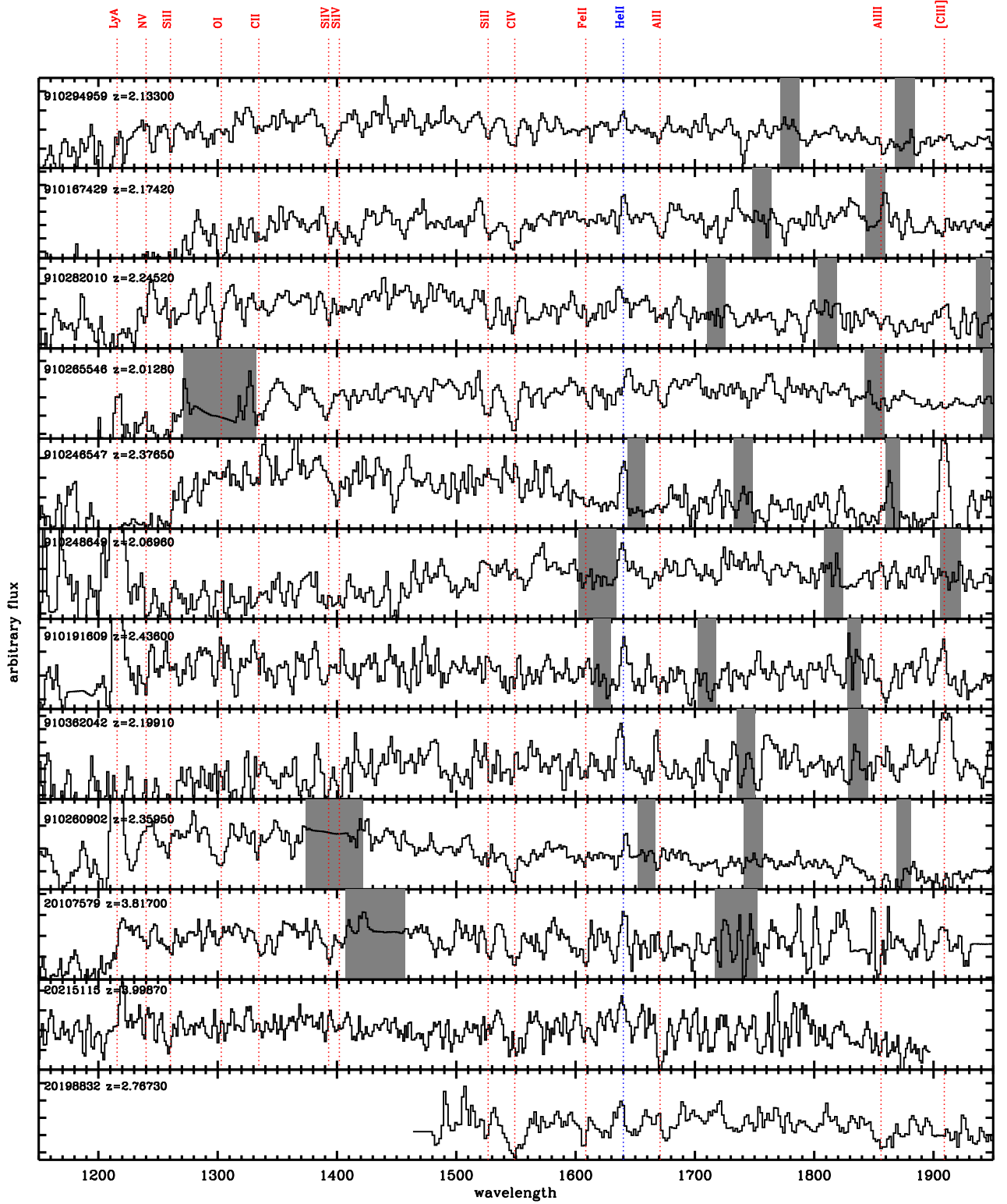


Fig. 2. Spectra of the high quality He II emitters with narrow He II emission ($\text{FWHM} < 1000 \text{ km/s}$). The grey strips show regions of the spectra that are contaminated by strong skylines or zero orders. We also report for each galaxy the id, the velocity difference between the He II and the systemic redshift, the width (FWHM) of the He II line and the systemic redshift.

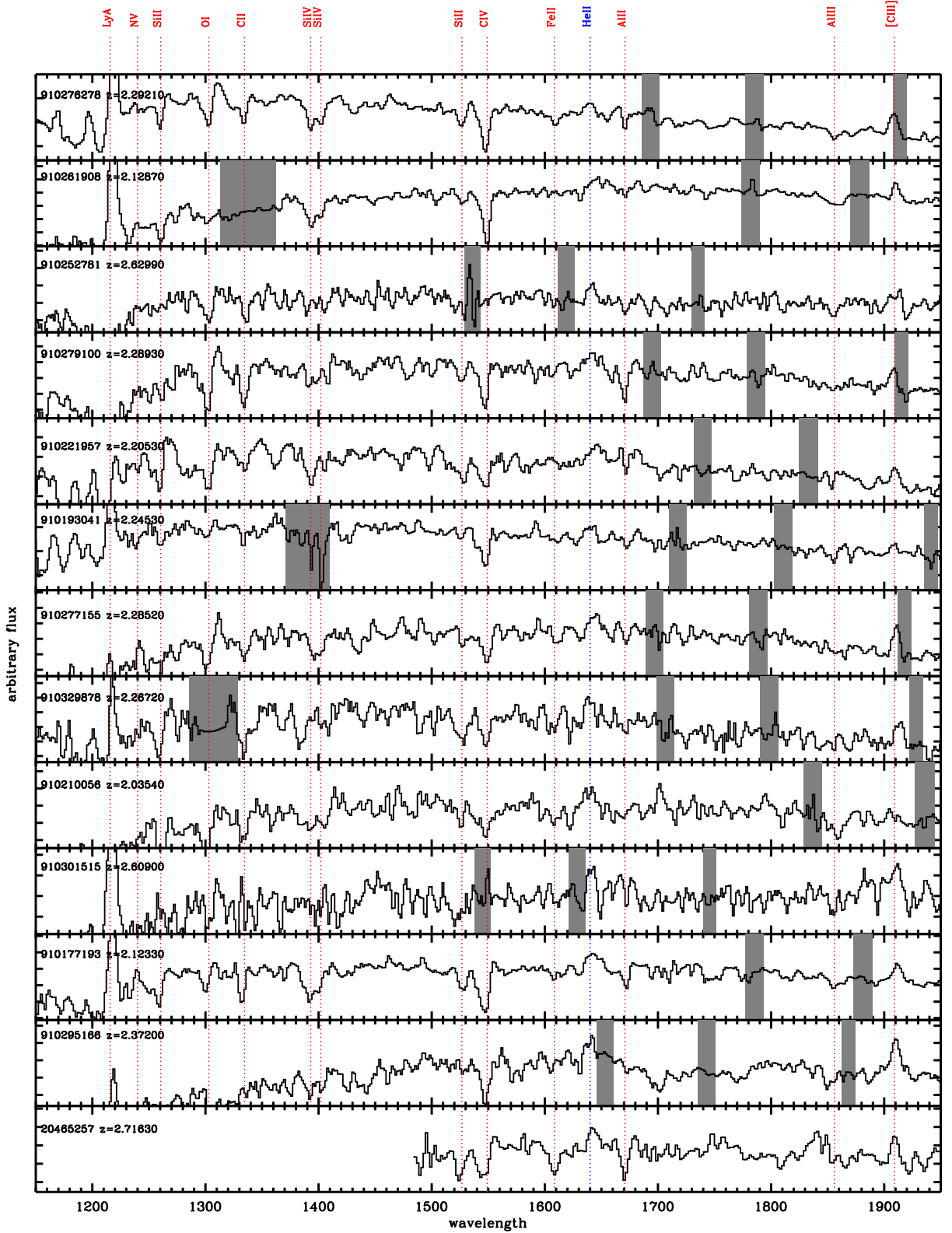


Fig. 3. Spectra of the high quality He II emitters with broad He II emission ($\text{FWHM} > 1800 \text{ km/s}$). The grey strips show regions of the spectra that are contaminated by strong skylines or zero orders. We also report for each galaxy the id, the velocity difference between the He II and the systemic redshift, the width (FWHM) of the He II line and the systemic redshift.

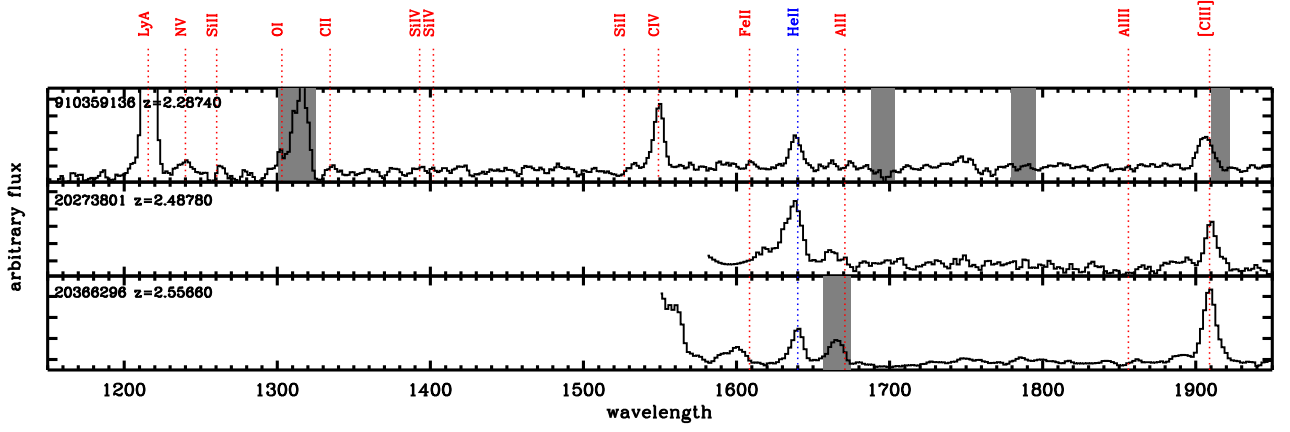


Fig. 4. Spectra of the AGN with He II emission. The grey strips show regions of the spectra that are contaminated by strong skylines or zero orders. We also report for each galaxy the id, the velocity difference between the He II and the systemic redshift, the width (FWHM) of the He II line and the systemic redshift.

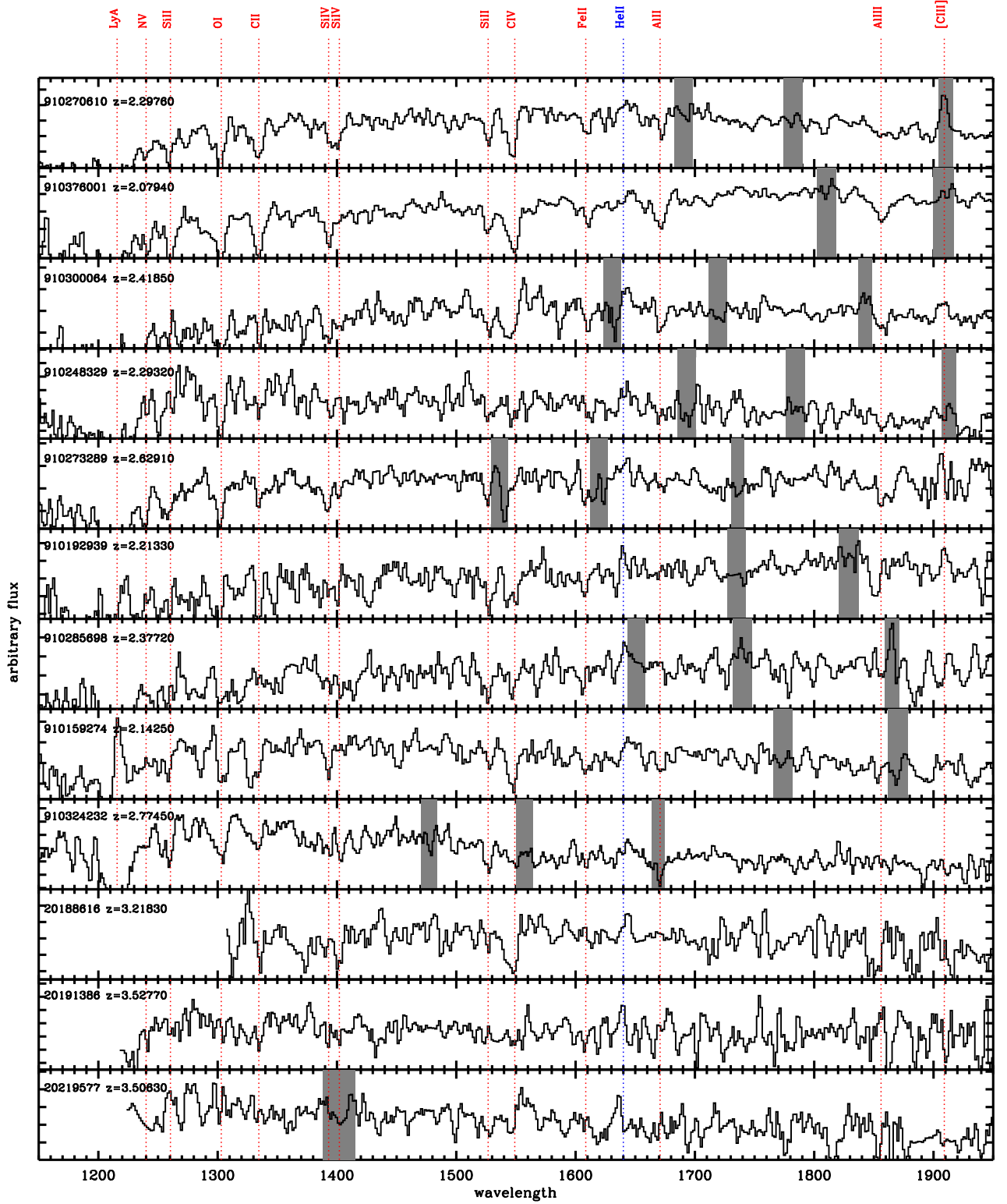


Fig. 5. Spectra of the possible He II emitters. The grey strips show regions of the spectra that are contaminated by strong skylines or zero orders. We also report for each galaxy the id, the velocity difference between the He II and the systemic redshift, the width (FWHM) of the He II line and the systemic redshift.

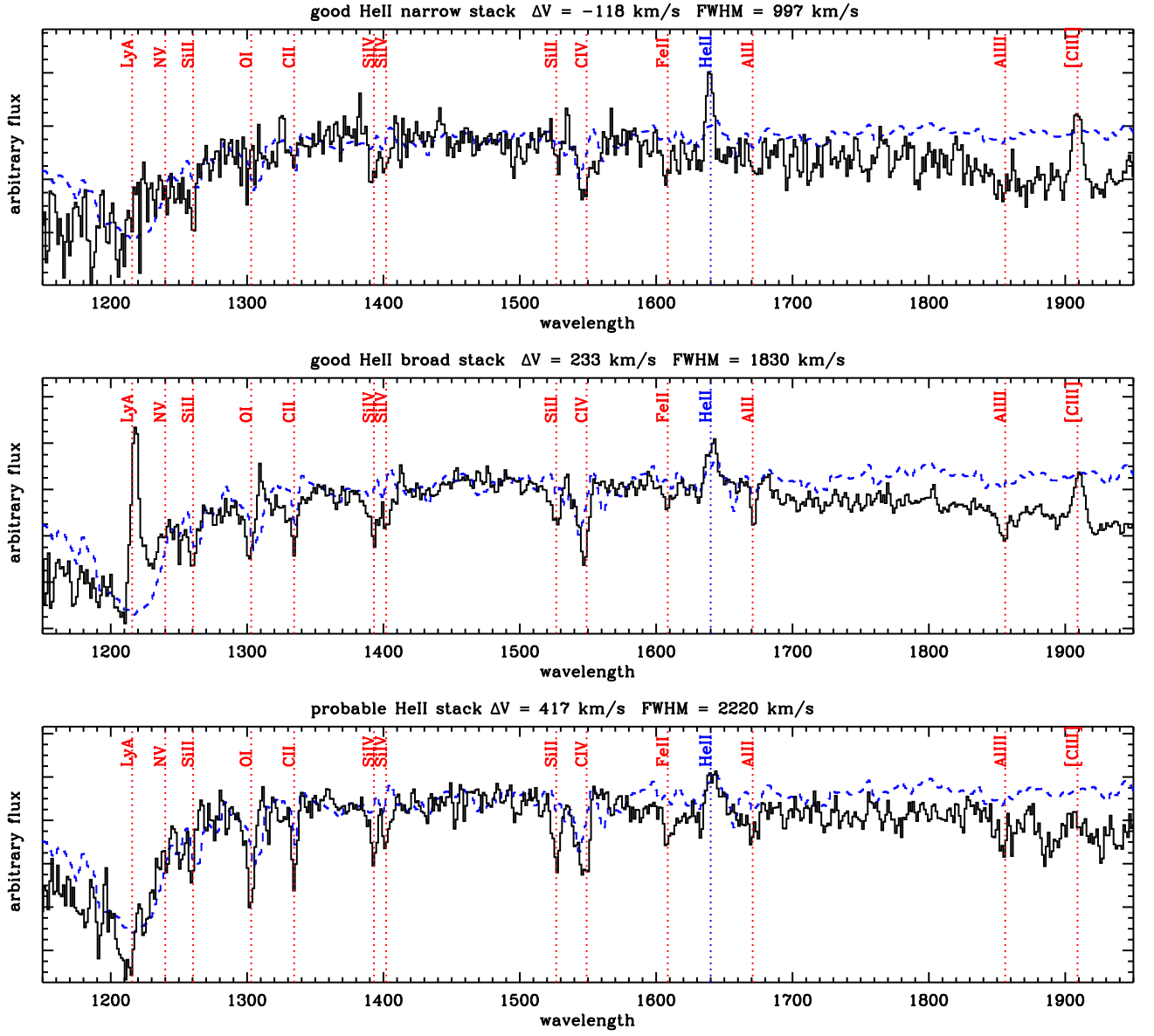


Fig. 6. Stack of the individual spectra for the high-quality galaxies with narrow He II emission (top), the high-quality galaxies with broad He II emission (middle) and the possible He II emitters (bottom). The blue lines show models obtained combining the predictions for a burst of star-formation by Maraston et al. (2009) with the predictions for a Wolf-Rayet phase by Eldridge & Stanway (2012). As explained in the text, they are not an attempt of fitting the composite spectra with models, but rather are aimed at comparing some spectral features in the composite spectra with the models.